

ELECTRICAL BREAKDOWN AND STREAMER STATISTICS IN N-HEXANE UNDER UNIFORM FIELD CONDITIONS

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ABSTRACT

Under uniform field conditions, two modes of electrical breakdown are observed in liquid n-hexane: breakdown may be initiated by either cathode or anode streamers. This observation suggests that two unique sets of phenomena lead to electrical breakdown. In the work described, high-speed photography is employed to obtain a record of each breakdown event thereby providing statistical information regarding the relative frequencies of anode and cathode processes. The degree to which the relative probability for either process is influenced by experimental conditions is discussed.

INTRODUCTION

Dielectric strength measurements in liquid dielectrics often yield widely varying results. The effects of electrode and liquid conditioning have long been recognized as a source of this variability [1]. It has not been possible, heretofore, to characterize one of the principle sources of such variability: the initiation voltage and speed of propagation of prebreakdown streamers differ according to whether initiation is from the cathode or the anode.

Dielectric breakdown is initiated by the propagation of a streamer in the liquid. Much progress has been made in describing the propagation of streamers in liquid dielectrics. The effect of differing materials, pressure and additives on electrical breakdown have received thorough investigation [2]. For liquid hydrocarbons, distinct modes of propagation are observed for both anode and cathode streamers [3]. For example, the speed of propagation of the cathode streamer at its inception differs dramatically from that at its final stage of growth and suggests significantly different propagation mechanisms. These results have been obtained, for the most part, in nonuniform fields where initiation occurs at a single electrode.

For impulse voltages, two modes of breakdown are observed in liquid n-hexane under uniform field conditions. The methods employed in the present study allow a photographic record of the conditions that exist in the liquid prior to electrical breakdown to be obtained. Conditioning of the liquid is found to have a robust effect on the relative abundance of cathode-streamer-initiated breakdowns. Such data allow systematic investigation of dielectric breakdown and are relevant to specifying reliable methods for the evaluation of liquid dielectric materials.

EXPERIMENTAL METHODS

The results discussed are obtained for quasi-uniform fields. As shown in Fig. 1, a high-voltage impulse is applied to a test gap and a record of the voltage waveform and framing photographs are obtained concurrently. The refractive index of prebreakdown streamers differs from that of the bulk liquid, thus allowing a shadow of the streamer to be recorded photographically. Frame photographs of the prebreakdown streamers provide a detailed record of their temporal development and are the basis for the assignment of the breakdown mode discussed below.

The test gap is composed of two stainless steel electrodes having 1.27 cm radius of curvature and spaced at 3.0 mm. The gap is enclosed within a cell filled with the liquid of interest.

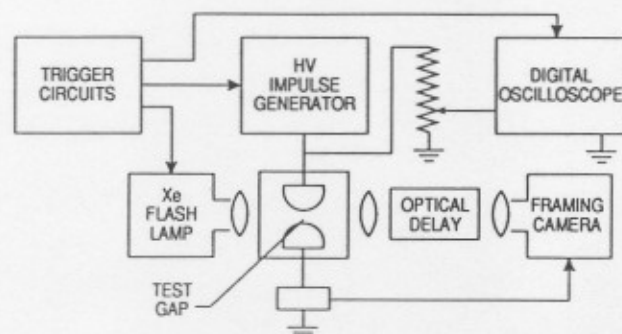


Figure 1. Schematic of the experimental apparatus.

Windows are provided in the cell through which the test gap is photographed. A xenon flashlamp provides illumination during application of the HV impulse.

Ultra-pure n-hexane is employed in this study. The liquid is used as received without further degassing or purification. To prevent the accumulation of particulate material, the fluid is circulated and filtered through a 2 μ m pore filter after each breakdown.

The impulse voltage is produced by a simulated transmission line and an impulse transformer. The peak voltage and the rate of rise of the impulse are controlled by the configuration of the pulse forming network and by varying the charging voltage. Two voltage waveforms were examined and are shown in Fig. 2. A fast impulse is shown in curve (A), and in curve (B) the slow impulse is plotted. The curves shown are obtained for the same charging voltage. A typical breakdown waveform is shown in curve (C). The breakdown time delay, t_{BD} , breakdown voltage, V_{BD} , and peak voltage, V_P , are measured by means of a resistive divider and digital oscilloscope.

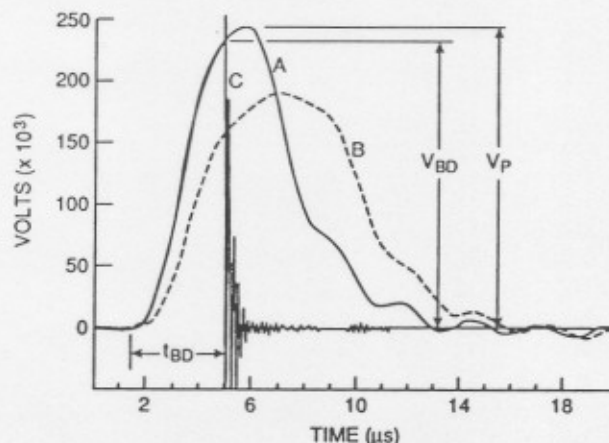


Figure 2. Representative voltage waveforms. The fast and slow impulse waveforms are plotted in curves (A) and (B), respectively. The peak voltage, V_P , breakdown voltage, V_{BD} , and breakdown time delay, t_{BD} , are also shown. A breakdown waveform is plotted in curve (C).

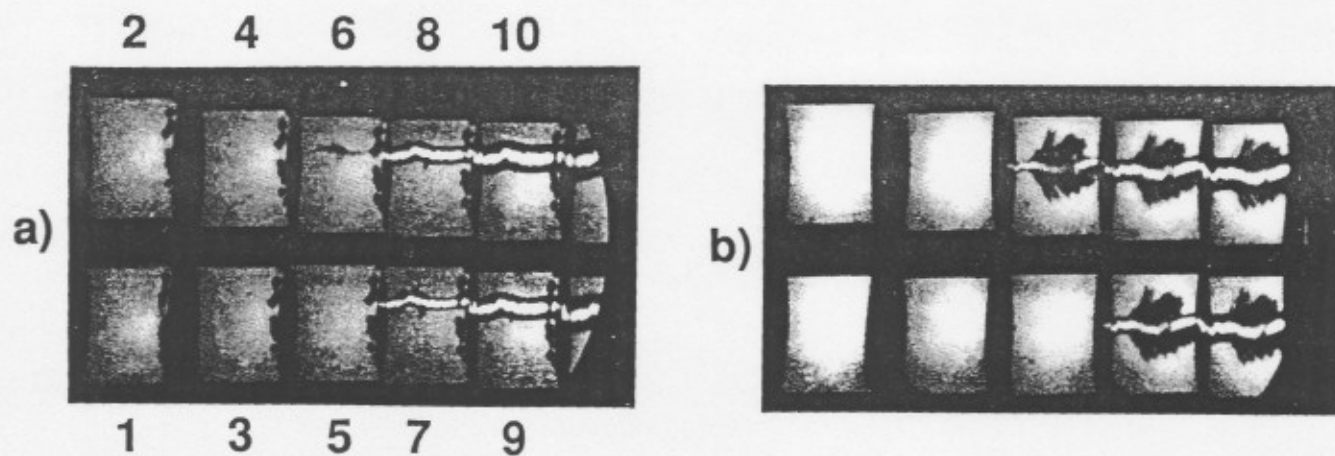


Figure 3. Frame photographs of cathode-streamer-initiated breakdown are shown in (a). The frame photographs shown in (b) are typical of anode-mode breakdown. The frame interval and exposure times are 50 and 10 ns, respectively. The frame sequence is indicated in (a). The anode surface is on the left.

An image-preserving optical delay [4] is used in conjunction with the fast-framing camera. As shown in Fig. 1, the framing camera is triggered by the breakdown current; however, since the optical delay (~ 400 ns) is greater than the trigger delay of the camera (~ 105 ns), conditions within the gap which precede breakdown are photographed. Since the prebreakdown phenomena are photographed for every breakdown, a systematic examination of streamer development is possible.

STREAMER MORPHOLOGY

Examples of dielectric breakdown are shown in Fig. 3. The photographs are obtained under identical experimental conditions. The nominal frame interval and exposure times are 50 and 10 ns, respectively, and the frame sequence is shown in photo (a). In all of the photos the anode surface is on the left.

Two distinct modes of breakdown are evident in the photographs. In Fig. 3(a) breakdown follows soon after the propagation of a cathode streamer across the gap. The morphology of the cathode streamers observed here is similar to that reported for nonuniform fields [3]. During their early growth, cathode streamers have a characteristic bush structure and propagate at subsonic speeds. Multiple cathode bush structures are clearly evident along the cathode surface in Fig. 3(a). The presence of the cathode bush is necessary but not sufficient for breakdown by a cathode streamer. In the present experimental conditions, breakdown is initiated by a fast growing, supersonic, secondary streamer which originates at one of the primary cathode streamers.

Although the temporal development of the prebreakdown streamer is not resolved in Fig. 3(b), the form of the disturbance surrounding the breakdown channel suggests that the initiating streamer originated at the anode. Under uniform field conditions, anode streamer propagation is rapid, and it is difficult to capture the development of the prebreakdown streamer even at the fastest framing rates. However, a record of the anode streamer may be constructed by interleaving photographs obtained at dif-

fering camera time delays; such a record is shown in Fig. 4. The photographs shown are obtained by increasing the camera delay by increments of 5, 10, 20, 30, and 40 ns. Frames shown in the figure that are separated by 50 ns are taken from the same photo.

The morphological stages evident in the anode streamer development are similar to those reported for nonuniform fields [3]. At the earliest times, a single linear streamer extends from the anode into the gap. The single streamer undergoes an abrupt transition to what appears to be densely packed, nearly linear filamentary streamers. The mean apparent length of first stage streamers at the transition to multiple streamers is 0.4 mm with $\sigma \approx 0.1$ mm. The streamers in the second stage of growth lie within a roughly conical volume with its apex on the line of the initial streamer. The main stroke develops soon after the prebreakdown streamer has propagated across the gap.

The photographs shown in Fig. 4 summarize a sample consisting of 25 trial impulses at each time delay and are obtained for the fast voltage waveform. The rise time of the impulse is 2.2 μ s (10–90%) and the peak voltage is 250 kV. The breakdown probability determined for the sample is 81%. The mean time delay and breakdown voltage are 4 μ s and 194 kV, respectively. These photos show the gap to be completely clear of anode streamers 30 ns before breakdown. The data at hand allow an estimate of the average speed of propagation and yield 1.0×10^7 cm/s.

Previous studies have shown the conductivity of streamers to be significantly higher than that of the bulk liquid [8]. This observation may have significance to the anode streamer propagation. If it is assumed that the anode streamer is a conductor of radius 20 μ m projecting into the gap 0.4 mm, a numerical calculation [5] shows that the field at the streamer tip is enhanced by a factor of 18. The mean electric field within the gap just prior to breakdown is 650 kV/cm. Thus, the field at the tip of the anode stem may reach levels sufficient for field-assisted ionization processes to become significant, and suggests that the transition to the more densely packed streamers appearing in the second stage

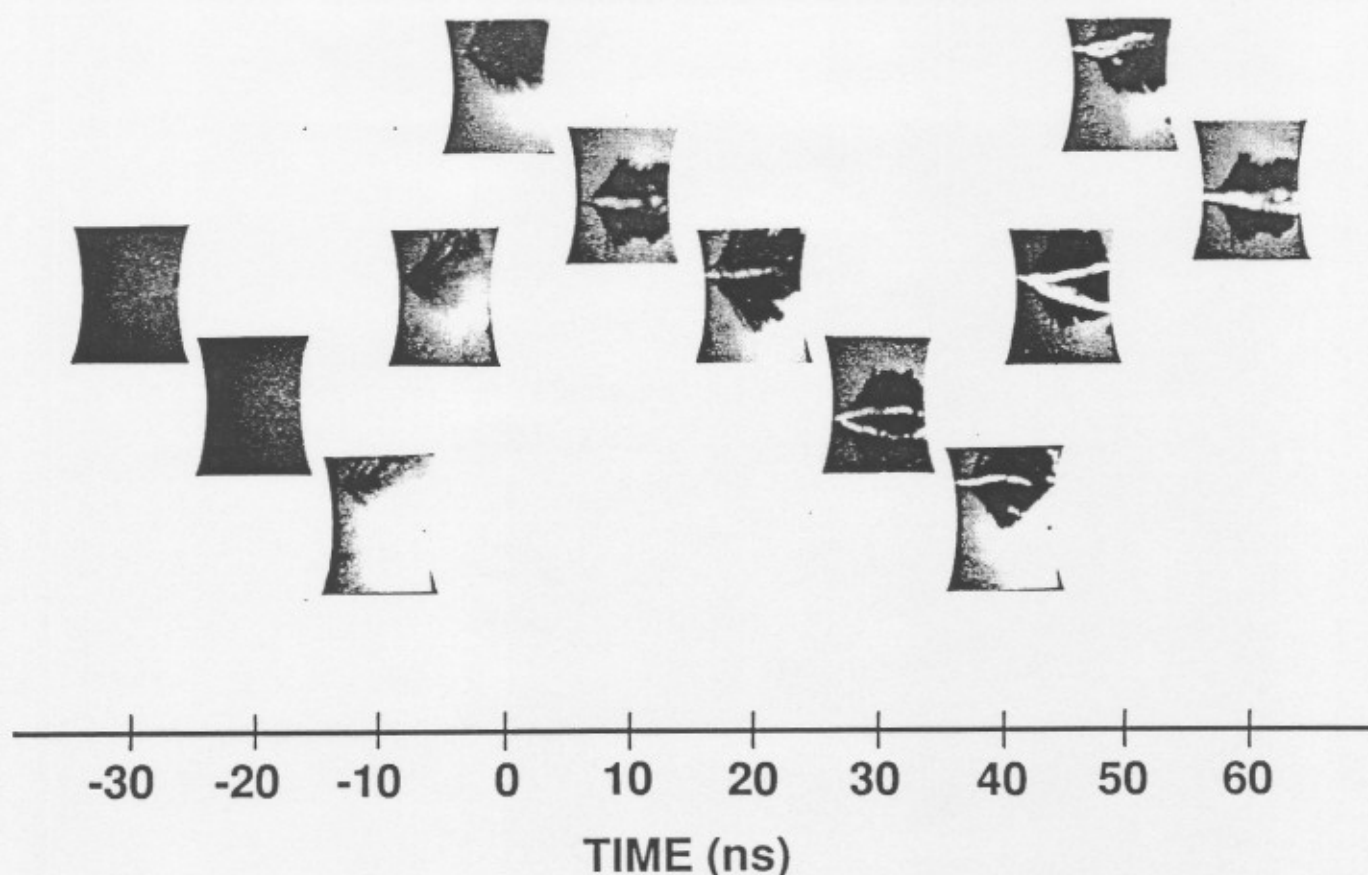


Figure 4. The temporal development of the anode streamer is shown. These photos are obtained by varying the camera delay by increments of 0, 5, 10, 20, 30, and 40 ns. Frames separated by 50 ns are from the same photograph. Time zero indicates the first evidence of a breakdown channel.

may be driven by such effects. It is noteworthy that the secondary cathode growth proceeds from a much shorter primary streamer and that the corresponding fields are much lower.

The temporal and spatial descriptions of the anode and cathode initiated breakdowns are distinct, and the mode of breakdown may be readily determined from the photographs. We make reference here to each as the anode or cathode modes, respectively. In the remainder of this report, tests undertaken to identify the experimental conditions which influence the relative probability for each mode are discussed.

RESULTS AND DISCUSSION

The influence of the voltage waveform and peak voltage were examined first. Using the fast impulse, the peak voltage was varied from threshold to that sufficient for 100% breakdown. Within these limits, the incidence of the cathode-initiated breakdown is 2%. For the slow waveform the cathode mode fraction is found to be approximately 12%, significantly larger than that for the fast pulse. However, anode streamer initiated breakdown is predominant for both waveforms. This observation may be anticipated from results for n-hexane obtained in a nonuniform fields which

show breakdown strengths for a point anode to be less than those for a point cathode [6]. The initial stage of cathode streamer growth is, however, clearly evident in 66% of the photographs.

To date, the accumulation of breakdown byproducts within the liquid has been found to have the most dramatic effect on the breakdown mode. To test for the influence of byproducts, the liquid was not circulated or filtered and was subjected to numerous breakdowns. The results of these tests are summarized in Fig. 5 where the breakdown probability and the cathode-mode fraction are plotted as functions of the number of breakdowns. Data obtained for both waveforms are shown.

The conditions which influence the transition to fast growing cathode streamers are not well understood. It has been suggested that the transition may be more likely at high overvoltages [7]. However, these results indicate that the formation of the secondary cathode streamer is more likely for the slow pulse at low peak voltage and that the cathode mode fraction increases dramatically with the addition of particulate material in the liquid. An increase in the breakdown probability with the accumulation of breakdown byproducts is also noted.

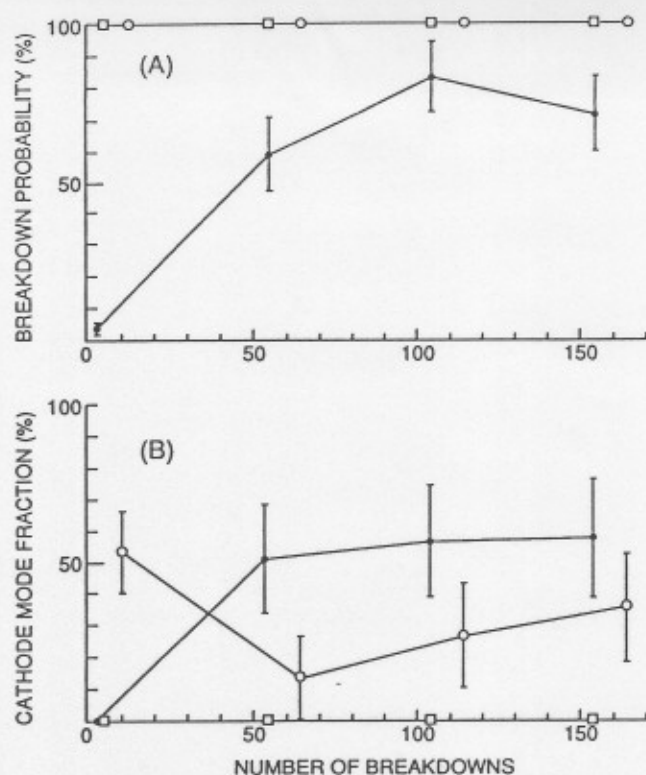


Figure 5. The breakdown probability and cathode mode fraction are plotted as functions of the total number of breakdowns. Data for the fast impulse □, peak voltage of 280 kV; and for the slow pulse, peak voltages of 220 kV ○ and 190 kV ● are plotted.

CONCLUSIONS

Methods have been developed which allow systematic study of pre-breakdown streamers in liquid dielectrics. In uniform fields under impulse conditions, breakdown may be initiated by either anode or cathode streamers. The relative probability for each mode of breakdown depends on the voltage waveform and is highly dependent on the presence of particulate material in the liquid. The variability observed in previous breakdown studies can be understood, in part, as a consequence of this underlying mechanism of mode selection.

ACKNOWLEDGEMENTS

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